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Changes in Long-Term No-Till Corn Growth and Yield under Different Rates of Stover Mulch

Humberto Blanco-Canqui,* R. Lal, W. M. Post, and L. B. Owens

ABSTRACT

Removal of corn (*Zea mays* L.) stover for biofuel production may affect crop yields by altering soil properties. A partial stover removal may be feasible, but information on appropriate rates of removal is unavailable. We assessed the short-term impacts of stover management on long-term no-till (NT) continuous corn grown on a Rayne silt loam (fine loamy, mixed, active, mesic Typic Hapludults) at Coshocton, Hoytville clay loam (fine, illitic, mesic Mollic Epiaqualfs) at Hoytville, and Celina silt loam (fine, mixed, active, mesic Aquic Hapludalfs) at South Charleston in Ohio, and predicted corn yield from soil properties using principal component analysis (PCA). The study was conducted in 2005 on the ongoing experiments started in May 2004 under 0 (T0), 25 (T25), 50 (T50), 75 (T75), 100 (T100), and 200 (T200)% of stover corresponding to 0, 1.25, 2.50, 3.75, 5.00, and 10.00 Mg ha^{-1} of stover, respectively. Stover removal promoted early emergence and rapid seedling growth ($P < 0.01$). Early-emerging plants grew taller than late-emerging plants up to about 50 d, and then the heights reversed at Coshocton and were comparable at other two sites. Stover management affected corn yield only at the Coshocton site where average grain and stover yields in the T200, T100, T75, and T50 (10.8 and 10.3 Mg ha^{-1}) were higher than those in the T0 and T25 treatments (8.5 and 6.5 Mg ha^{-1}) ($P < 0.01$), showing that stover removal at rates as low as 50% (2.5 Mg ha^{-1}) decreased crop yields. Soil properties explained 71% of the variability in grain yield and 33% of the variability in stover yield for the Coshocton site. Seventeen months after the start of the experiment, effects of stover management on corn yield and soil properties were site-specific.

Biofuel production from renewable energy sources is among the potential strategies to reduce the use of nonrenewable fuel sources and net CO_2 emissions (Lal, 2005; Pacala and Socolow, 2004). Corn stover is an attractive biofuel feedstock source because of its abundance and high lignocellulosic contents (Johnson et al., 2004; Sedlak and Ho, 2004). Producing biofuel from corn stover can be a beneficial alternative to fossil fuels. Also, stover marketing for biofuel production could provide additional economic benefits to farmers. However, stover removal effects on subsequent crop production and soil productivity are not well documented. Because stover left on the soil surface impacts soil water and temperature regimes, radiation balance, nutrient cycling, and soil structural attributes essential to plant growth, excessive stover removal may reduce crop yields (Wilhelm et al., 2004).

In some ecosystems, a partial removal of stover for energy production may be a viable option. The unresolved question is, however, how much corn stover can be removed for ethanol production without negatively affecting crop production and soil productivity? While some estimates of stover removal for biofuel production based on the requirements to reduce soil erosion in the U.S. Corn Belt region are available (Larson et al., 1978; Nelson, 2002; Kim and Dale, 2004), data on the threshold levels of stover removal needed to sustain crop production have not been well documented. Local and regional guidelines are needed for recommendation on the maximum permissible rates of stover removal based on data from well-designed experiments. A balance between stover removal for biofuel production and stover retention for soil and water conservation in relation to crop productivity needs to be established for site-specific conditions.

While the importance of crop residue mulch for soil and water conservation is widely recognized, the data on the effects of residue removal or addition on corn yield can be variable. In some soils, high stover retention in NT soils can negatively affect corn growth and yield. On Rozetta (fine-silty, mixed, superactive, mesic Typic Hapludalfs) and Palsgrove (fine-silty, mixed, superactive, mesic Typic Hapludalfs) silt loams in southwestern Wisconsin, corn yield decreased when stover cover was doubled (Swan et al., 1994). On a Marshall silty clay loam (fine-silty, mixed, superactive, mesic Typic Hapludolls) in Iowa, corn yield decreased during the last 4 yr of a 13-yr continuous corn system with the addition of 2, 4, 8, and 16 Mg ha^{-1} of stover mulch (Morachan et al., 1972). The lower corn yields, in some soils, may be due to slow soil warming during germination, low pH, nutrient immobilization, and high incidence of weeds and pests under high rates of stover mulch (Mann et al., 2002). Conversely, on a Crete-Butler silty clay loam (fine, smectitic, mesic Pachic Argiustolls) (<2% slope) in Nebraska, complete removal of stover from the soil surface of a 4-yr NT system reduced the corn grain and biomass yields by about 23% (Wilhelm et al., 1986; Power et al., 1998). On a Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludolls) in Minnesota, stover removal reduced corn yield by 1 Mg ha^{-1} during 3 of a 12-yr NT continuous corn system (Linden et al., 2000). On a Raub silt loam (fine-silty, mixed, superactive, mesic Aquic Argiudolls) in Indiana, differences in corn yield under 6-yr

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Abbreviations: CI, cone index; MWD, mean weight diameter of aggregates; NT, no-till; PCs, principal components; PCA, principal component analysis; SHEAR, shear strength; SWRC, soil water retention characteristics; SOC, soil organic carbon; TS, tensile strength.

NT continuous corn with stover returned, removed, and doubled were not, however, significant (Barber, 1979). Previous studies show that corn yield can increase, remain unaffected or decrease with increase in stover removal and underscore the need for clarification of stover removal impacts on corn yield. These data suggest that stover removal impacts on corn production depend on site-specific characteristics such as soil, topography, duration of stover management history, tillage, and climate. Thus, threshold levels for stover removal as biofuel must also be site-specific.

Changes in soil water content, temperature, and strength as a result of stover removal can alter soil conditions and impact corn emergence and growth (Sharratt, 2002). In fact, changes in near-surface soil physical properties by stover removal can be significant even within 1 yr following removal (Blanco-Canqui et al., 2006). Dabney et al. (2004) asserted that benefits of long-term NT management may be lost by removing crop residue. The hypothesis is that rapid changes in soil properties due to stover removal may also induce changes in corn growth and yield within a short period after stover removal even from a long-term NT system. Corn emergence can be particularly sensitive to changes in soil water and temperature regimes (Ford and Hicks, 1992). Uneven seed emergence and plant height can affect corn yield (Nafziger et al., 1991). Liu et al. (2004) reported that a delayed corn emergence due to slow soil warming in spring in mulched soils reduced grain yields by 35 to 50% compared with unmulched soils. In some mulched soils, the negative effects of delayed emergence on growth may be offset by improved nutrient and water supply and reduced soil crusting, but these counteracting processes across a range of soils need to be quantified. Literature is replete with studies on the combined effects of tillage, cropping systems, and residue management on crop yields (Lal et al., 2000; Pikul et al., 2001). Independent effects of a systematic removal of stover on corn grain and stover yields under long-term NT systems for the Corn Belt region have not, however, been studied extensively. Thus, research data are needed to determine threshold levels of stover removal. Understanding of the short-term impacts of stover removal on corn production is important to developing stover management strategies to meet energy and crop production needs.

Crop production depends largely on the complex interactions among dynamic and static soil properties. The PCA, a multivariate statistical approach, is a potential tool to identify the most sensitive soil attributes influencing crop yields (Jiang and Thelen, 2004). Studies assessing stover management-induced changes in soil properties in relation to corn grain and stover production using PCA are limited. Statistical tools such as PCA can also predict changes in yield based on critical soil properties. Hence, the objectives of this study were to: (i) quantify the impacts of stover removal and addition on corn growth and grain and stover yields across three principal soils in Ohio under NT continuous corn management, (ii) establish interrelationships between corn growth parameters and soil water and temperature regimes as affected by stover management, and (iii) identify critical near-surface soil properties affecting corn yield using PCA.

MATERIALS AND METHODS

Site and Treatment Descriptions

The study was conducted on the ongoing long-term NT continuous corn experiments at three sites in Ohio. The project was initiated in 2004 to characterize the ramifications of corn stover removal on soil physical quality, hydrological and thermal properties, grain and stover yields, and soil organic carbon (SOC) concentration under NT continuous corn systems. The three experimental sites are: (i) North Appalachian Experimental Watersheds near Coshocton, (ii) Western Agricultural Experiment Station near South Charleston, and (iii) Northwestern Agricultural Experiment Station (NWAES) near Hoytville of the Ohio Agricultural Research and Development Center (OARDC). Soils among the three sites exhibit contrasting differences in texture, slope, and geology. Details of soil and management characteristics for the three sites are shown in Table 1.

A randomized complete block design with six treatments replicated three times for a total of 18 plots of 3 by 3 m was established at each site in early May 2004. The six treatments consisted of applying 0 (T0), 25 (T25), 50 (T50), 75 (T75), 100 (T100), and 200 (T200)% of corn stover on the soil surface, corresponding to 0, 1.25, 2.50, 3.75, 5.00, and 10.00 Mg ha^{-1} of stover, respectively. The individual plots have no permanent borders and are demarcated by marking flags at the corners. Corn was planted in each plot during May 2004 and 2005, and any stover shift caused by the planting operations was redistributed in each specific plot. The percent stover mulch cover

Table 1. Soil and management characteristics of the three experimental sites in Ohio.

Study sites	Coordinates	Soil series	Taxonomic classification	Soil description	Slope	Management history
					%	
North Appalachian Experimental Watersheds, Coshocton	40°16′19″ N, 81°51′35″ W	Rayne silt loam (638 g kg^{-1} silt and 153 g kg^{-1} clay)	fine loamy, mixed, active, mesic Typic Hapludults	deep and well drained soils formed from weathered shale and fine-grained sandstone	10	35-yr no-till continuous corn, 150 kg N ha^{-1} yr^{-1} applied as NH_4NO_3, and herbicides applied for controlling weeds
Western Agricultural Experiment Station, South Charleston	39°49′31″ N, 83°38′04″ W	Celina silt loam (558 g kg^{-1} silt and 216 g kg^{-1} clay)	fine, mixed, active, mesic Aquic Hapludal	very deep, moderately well drained and formed in high-lime loamy glacial till plains and moraines	2	15-yr no-till continuous corn–soybean rotation
Northwestern Agricultural Experiment Station, Hoytville	41°11′24′ N, 83°47′05″ W	Hoytville clay loam (341 g kg^{-1} silt and 437 g kg^{-1} clay)	fine, illitic, mesic Mollic Epiaqual	these soils are on nearly level, till-floored lake plains, very deep, and very poorly drained	<1	8-yr continuous corn–soybean rotation under no-till with alternate year disking

in each plot was estimated using the line-transect method (Sloneker and Moldenhauer, 1977). Each plot comprises four rows of corn spaced 0.75 m apart. Corn stover was redistributed immediately following harvest in the corresponding treatments in October 2004 and 2005. This study reports data on corn growth characteristics for the 2005 growing season from May to July and corn yield at 17 mo after the start of the experiment. There were no differences in corn growth or yield during 2004.

Measurement of Agronomic Characteristics

Seedling emergence, plant height, chlorophyll content, and corn grain and stover yields were determined in all treatments and sites during the 2005 growing season. Measurements of corn agronomic characteristics were done on the center two 3-m rows of each plot. Days to emergence after planting were monitored to determine possible emergence delays due to the level of stover retention. Plant height was determined by measuring the distance from soil surface to growing tip of corn every week from emergence to silking (Ritchie and Hanway, 1982). Leaf chlorophyll content was measured by a Minolta SPAD 502 chlorophyll meter (Spectrum Technol., East-Plainfield, IL) to estimate differences in leaf N concentration among treatments given that N is a main element in chlorophyll molecules. The SPAD readings were obtained from the uppermost fully developed leaves without lesions for 30 plants per treatment at 50 d after emergence. At physiological maturity, corn ears and stover from the center two rows were hand harvested and weighed in October 2005 to quantify grain and stover yields. Upon air-drying, corn ears were shelled, and kernels and cobs weighed separately. Subsamples of stover, kernel, and cob were weighed and then oven-dried at 65°C for 72 h to determine water content. Grain and biomass yields are reported at water content of 155 g kg^{-1}.

Measurement of Soil Properties

To explain any possible differences in corn yield among stover removal treatments, a number of dynamic soil properties were evaluated from emergence (May) to silking (July) stage during 2005. Soil temperature was monitored every other day from emergence up to 8 d following emergence and then once weekly thereafter. Dual thermocouple thermometer probes (Cole-Parmer Instruments, Co., Vernon Hills, IL; McInnes, 2002), inserted at the 5- and 10-cm soil depths, were used to record temperature at 1400 h. Volumetric soil water content (θ_v) based on the gravimetric water content (Topp and Ferré, 2002) and bulk density (ρ_b) determined by the core method (Grossman and Reinsch, 2002) were measured weekly on intact small 5.4- by 6-cm soil cores, extracted from 0- to 6-cm depth. Soil strength parameters such as cone index (CI) and shear strength (SHEAR) were measured monthly for the 0- to 5-cm depth. A static hand cone penetrometer (Eijkelkamp, Giesbeek, the Netherlands) was used to measure soil penetration resistance (Lowery and Morrison, 2002), and a CL-612 shear vane tester (ELE International, Lake Bluff, IL; Serota and Jangle, 1972) was used to measure the SHEAR. In July 2005, 5.4- by 6-cm intact soil cores and bulk samples were collected from each plot for all sites to determine saturated hydraulic conductivity (K_{sat}) by the constant head method (Reynolds et al., 2002), soil water retention characteristics (SWRC) at −10kPa by the tension table and −30kPa by pressure plate extraction (Dane and Hopmans, 2002), air permeability (k_a) by the steady-state method (Ball and Schjønning, 2002), water-stable aggregates (WSA) by the wet-sieving procedure to compute mean weight diameter (MWD) (Nimmo and Perkins, 2002), tensile strength (TS) of 6- to 8-mm aggregates by the crushing method (Dexter and Watts, 2001), and total SOC concentration by the dry combustion method (900°C) using a CN analyzer (Vario Max, Elementar Americas, Hanau, Germany) (Nelson and Sommers, 1996).

Statistics

The two-factor ANOVA model was used to test whether: (i) treatment × block interaction was significant and (ii) stover management affected corn emergence, plant height, corn yield, and soil properties by site. The PCA was used to compute soil variance and to determine the most yield-influencing soil properties. Principal components with eigenvalues >1 were retained (Kaiser criterion) and then subjected to varimax rotation to identify potential determinants of crop yield using the FACTOR procedure in SAS (SAS Institute, 2005). The PCA loadings based on rotated scores, communality estimates, and scoring coefficients were used as a criteria to determine the influence of a given soil property on yield variability. Scoring coefficients of the PCs were used as independent variables to develop equations to predict grain and stover yields using stepwise multiple regression analyses. All statistical analyses were done using SAS.

RESULTS AND DISCUSSION

Corn Emergence and Plant Height

The two-factor ANOVA showed that the treatment × block interaction was not significant for any of the parameters measured at any of the three sites. Time to corn emergence was significantly affected by the removal and addition of stover 1 yr after experiment initiation ($P < 0.05$). Across all sites, the systematic removal of stover promoted early emergence, whereas doubling the amount of stover delayed emergence. Days to emergence after planting for each treatment and site were: 8 in T0 and T25, 9 in T50, 10 in T75, 11 in T100, and 13 in T200 plots at Coshocton; 9 in T0, T25, and T50, 11 in T75, 12 in T100, and 16 in T200 plots at Hoytville; 8 in T0 and T25, 9 in T50, 10 in T75, 11 in T100, and 13 in T200 plots at Charleston. Compared with the complete stover removal treatment (T0), the normal stover treatment (T100) delayed emergence by 3 d, while the T75 treatment delayed emergence by 2 d at Coshocton and Charleston and by 3 d at Hoytville. Doubling the quantity of stover from 100 (T100) to 200% (T200) delayed emergence by 2 d at Coshocton and Charleston and by 4 d at Hoytville compared with the T100 treatment. Thus, if 100% of stover was removed or added, corn emergence increased or decreased accordingly by about 3 d. Similar studies in temperate climates have also reported that increased stover cover hinders corn emergence (Mehdi et al., 1999).

Mean corn height as a function of stover management from emergence to silking is shown in Fig. 1. The significant differences in days to emergence, discussed earlier, had a direct effect on corn height. Early emerging plants grew consistently taller than the late emerging plants up to about 50 d following emergence. Early in the growing season, corn height decreased with increase in stover retention (Fig. 2). For example, 1 wk after emergence, variations in stover quantities explained >90% of the

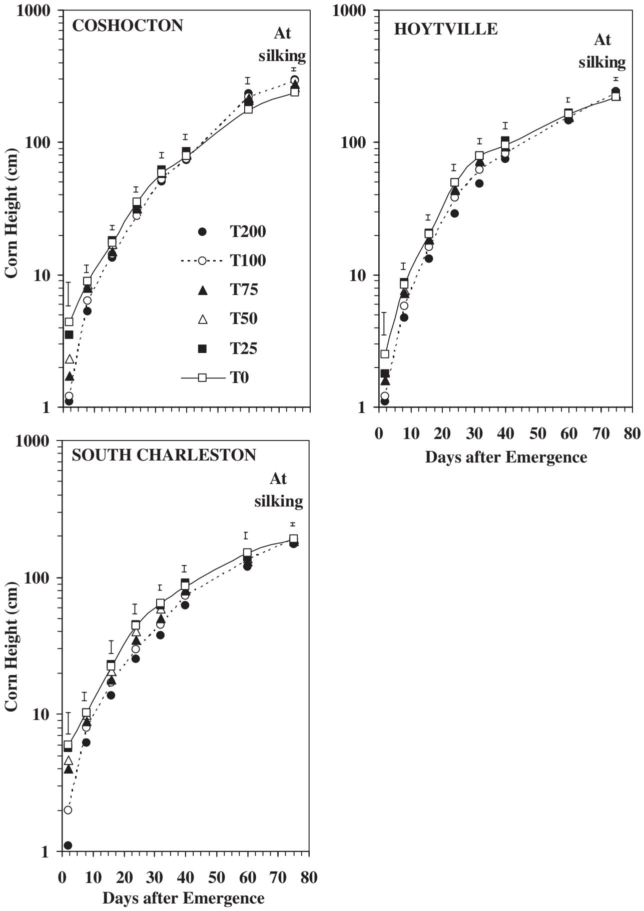

Fig. 1. Corn height as a function of days after emergence under six stover treatments for three no-till sites in Ohio including Coshocton, Hoytille, and South Charleston. The six treatments including 0 (T0), 25 (T25), 50 (T50), 75 (T75), 100 (T100), and 200 (T200)% of corn stover correspond to 0, 1.25, 2.50, 3.75, 5.00, and 10.00 Mg ha^{-1} of stover, respectively. The error bars represent the LSD(0.05) for treatment comparisons.

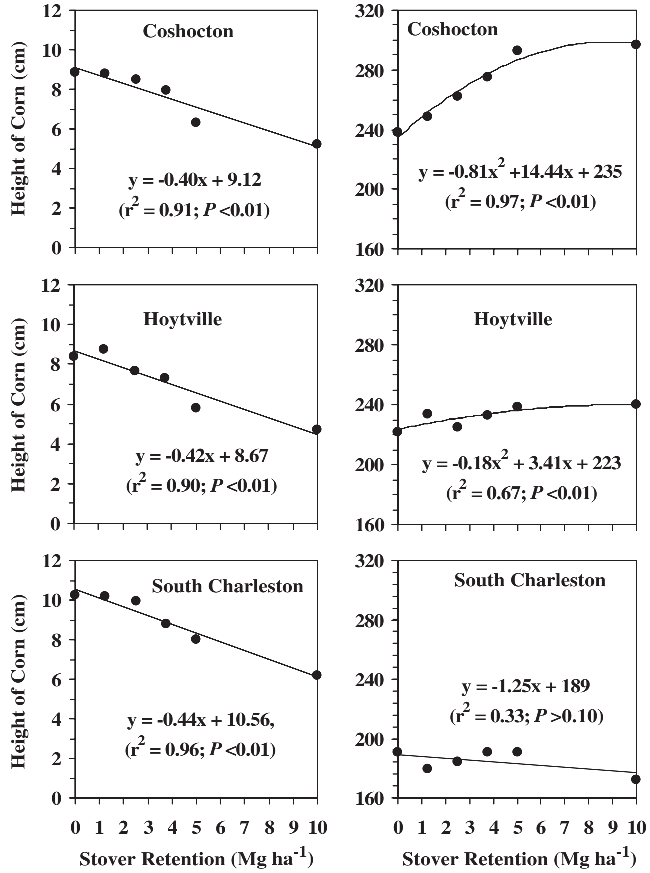

Fig. 2. Relationship between corn height and six stover rates (0, 1.25, 2.50, 3.75, 5.00, and 10.00 Mg ha^{-1}) at 8 d after emergence and silking stage under three no-till sites in Ohio.

variability in plant height at the three sites ($P < 0.01$). However, the magnitude of differences in height diminished rapidly with time. In fact, at about 50 d following emergence, corn height evened out at all sites, and thereafter the impact of residue on corn height was gradually reversed particularly at Coshocton. Contrary to early stages, corn under the T75 and the T100 treatments grew consistently taller than that under T0 and T25 at Coshocton and slightly at Hoytville. At silking, corn height increased in direct proportion to stover retention at all but the Charleston site where differences in height among treatments were unaffected ($P > 0.10$). These results indicate that stover retention can diminish corn emergence and plant height, but the early effects on height can be reversed depending on soil type.

Leaf chlorophyll SPAD readings at 50 d after emergence were not significantly different among stover treatments at any site. Mean readings were 40.9 ± 1.5 and 43.5 ± 1.2 at Coshocton, 44. 6 ± 2.5 and 47.8 ± 1.4 at Hoytville, and 36.6 ± 4.6 and 40.5 ± 4.3 at Charleston for the T100 to T200 and T0, T25, and T50 treatments, respectively. The slightly higher readings for the T0, T25, T50, and T75 treatments may be due to faster emergence and possibly to high stover mineralization relative to heavily mulched plots. Mehdi et al. (1999) also reported that NT corn with 100% of stover cover had lower SPAD readings than NT corn without stover, but differences in corn yield between the two treatments were nonsignificant in a loamy sand. These results warrant an intensive and long-term monitoring of leaf chlorophyll content to ascertain implications of stover removal on corn N content and status.

Corn Growth vs. Soil Water Content and Temperature Relationships

The uneven emergence and seedling height among treatments were directly attributed to stover cover effects on soil θ_v (Fig. 3) and temperature (Fig. 4). At all sites, soil θ_v decreased and temperature increased with increase in stover removal ($P < 0.01$). Soils under the T200, T100, and T75 treatments were wetter and colder than those under the T50, T25, and T0 treatments, which most likely delayed emergence. On the average, θ_v for the T100 and T75 treatments was higher than that for the T0, and T25, and T50 treatments by 40% at Coshocton, 60% at Hoytville, and 70% at Charleston for the dates measured between emergence and silking (Fig. 3). Differences in soil θ_v and temperature between the double stover treatment (T200) and normal stover treatment (T100) were generally not significant except

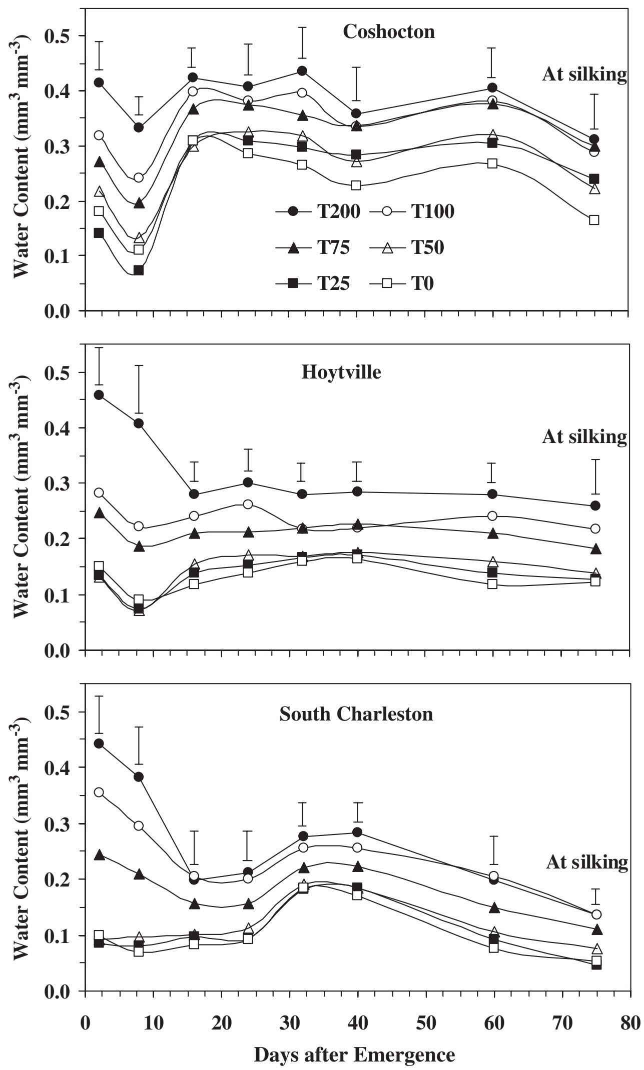

Fig. 3. Variations in soil water content from corn emergence to silking stage for three no-till sites in Ohio. The six treatments including 0 (T0), 25 (T25), 50 (T50), 75 (T75), 100 (T100), and 200 (T200)% of corn stover correspond to 0, 1.25, 2.50, 3.75, 5.00, and 10.00 Mg ha^{-1} of stover, respectively. The error bars represent the LSD(0.05) for treatment comparisons.

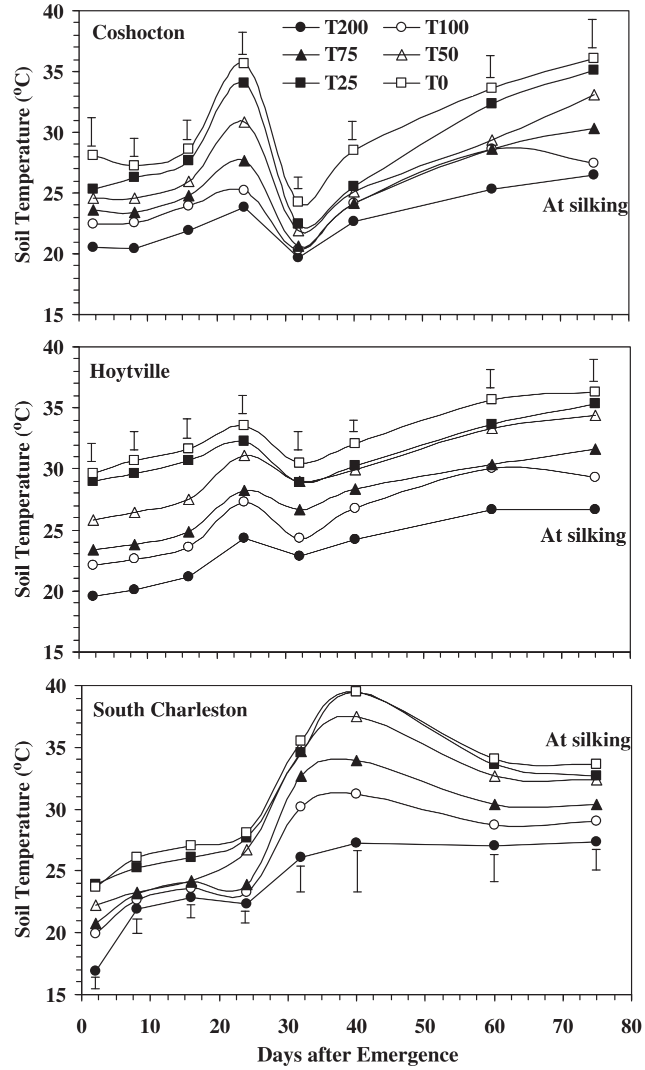

Fig. 4. Variations in soil temperature from corn emergence to silking stage for three no-till sites in Ohio. The six treatments including 0 (T0), 25 (T25), 50 (T50), 75 (T75), 100 (T100), and 200 (T200)% of corn stover correspond to 0, 1.25, 2.50, 3.75, 5.00, and 10.00 Mg ha^{-1} of stover, respectively. The error bars represent the LSD(0.05) for treatment comparisons.

during the first 10 d following emergence in which θ_v for T200 was higher by 34% at Coshocton, 60% at Hoytville, and 27% at Charleston. Stover removal of >25% (1.25 Mg ha^{-1}) increased soil temperature by 3 to 7°C from emergence to silking (Fig. 4).

At 8 d after emergence, corn height was positively correlated with soil temperature and negatively with θ_v (Fig. 5–6; $P < 0.01$). Soil temperature explained 67% of the variability in height at Coshocton, 77% at Hoytville, and 47% at Charleston, while soil θ_v explained 83% of the variability in plant height at Coshocton, 71% at Hoytville, and 72% at Charleston. At silking, trends in plant height were reversed, and corn height was negatively correlated with soil temperature and positively with θ_v except at Charleston where corn height was unaffected ($P > 0.10$) by stover treatments in spite of significant differences in soil θ_v and temperature (Fig. 5–6). At this stage, soil temperature explained 83 and 29% and θ_v explained 35 and 37% of the variability in height at Coshocton and Hoytville ($P < 0.01$), respectively. The contrasting correlations between the two sites may be due to differences in soil texture and topography. Changes in soil temperature and θ_v had apparently lesser effect on corn height in flat terrain and glaciated soils at Hoytville and Charleston than in sloping and unglaciated soils at Coshocton. Data show that the higher soil θ_v and lower temperature in the T200, T100, and T75 treatments delayed emergence but improved corn growth later in the season especially at Coshocton. Overall, these results show that changes in soil θ_v and temperature due to stover removal can have large impacts on corn emergence and growth in some soils.

Grain and Stover Yields

Means of corn grain and stover yields by treatment and soil are shown in Fig. 7A and 7B. Changes in stover

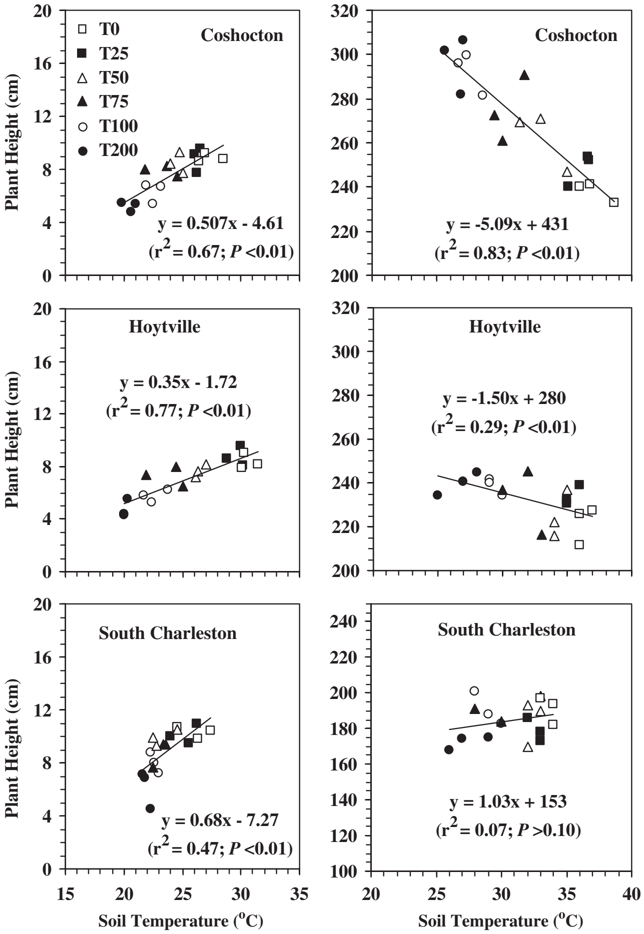

Fig. 5. Corn height as a function of changes in soil temperature for three no-till sites in Ohio. The six treatments including 0 (T0), 25 (T25), 50 (T50), 75 (T75), 100 (T100), and 200 (T200)% of corn stover correspond to 0, 1.25, 2.50, 3.75, 5.00, and 10.00 Mg ha^{-1} of stover, respectively.

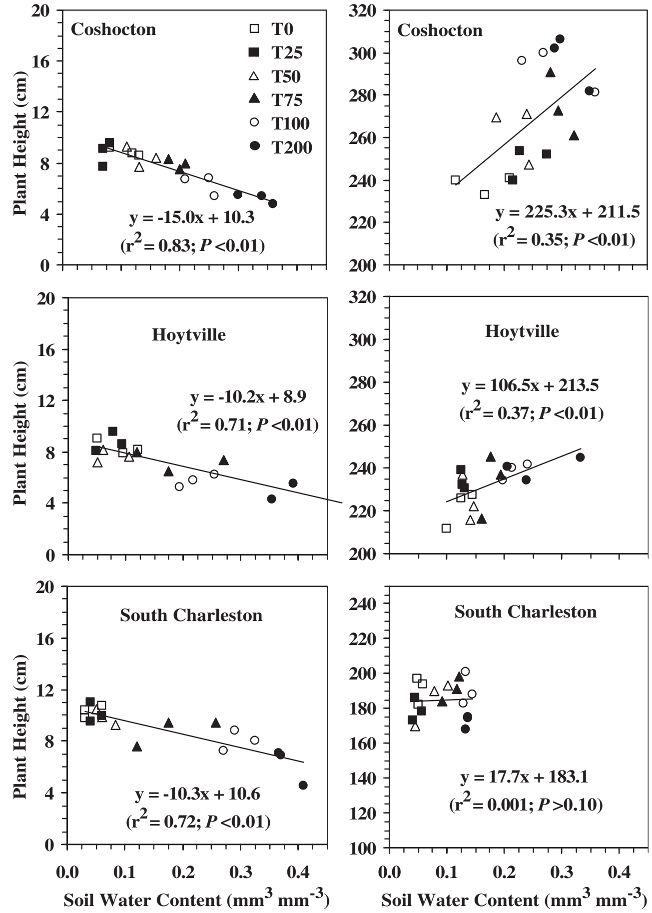

Fig. 6. Corn height as a function of changes in soil water content for three no-till sites in Ohio. The six treatments including 0 (T0), 25 (T25), 50 (T50), 75 (T75), 100 (T100), and 200 (T200)% of corn stover correspond to 0, 1.25, 2.50, 3.75, 5.00, and 10.00 Mg ha^{-1} of stover, respectively.

cover affected significantly the grain and stover yields at Coshocton but not at Hoytville and Charleston. Averaged across the six treatments, mean grain yield was 9.7 Mg ha^{-1} at Hoytville and 8.3 Mg ha^{-1} at Charleston, while mean stover yield was 7.4 Mg ha^{-1} at Hoytville and 6.1 Mg ha^{-1} at Charleston. At Coshocton, grain and stover yields increased quadratically with increase in stover mulch (Fig. 7A–7B). The quadratic functions show that rates of stover mulch explained 93% of the variability in grain yield and 95% in stover yield. Wilhelm et al. (1986) also showed that stover retention explained about 80% of the yield variability in corn grain and 86% in stover yields, attributed to improvements in soil water content and temperature regimes and input and cycling of nutrients. At Coshocton, differences in stover yield were not significant among the T200, T100, T75, and T50 treatments nor between the T0 and T25 treatments. Mean grain and stover yields averaged across the T50, T75, T100, and T200 treatments (10.8 and 10.3 Mg ha^{-1}) were significantly higher than that averaged across the T0 and T25 treatments (8.5 and 6.5 Mg ha^{-1}) ($P < 0.05$). Results for the Coshocton site show that 50% removal of stover (2.5 Mg ha^{-1}) can significantly decrease the grain and stover yields in these soils even within 1 yr after commencing the removal. Mean grain and stover yields in treatments T50 through T200 at this site were 24 and 58% higher than those across the T0 and T25 treatments, respectively. The decrease in stover yield was twice as much as that in grain yield, suggesting that stover removal may have larger effect on reducing stover yield than grain yield. At the same site, the quadratic functions in Fig. 7A and 7B show that changes in corn yield among the T75, T100, and T200 treatments were smaller than those in T0, T25, T50, and T75, illustrating a rapid reduction in yield by excessive stover removal.

Data show that short-term impacts of stover removal and addition on stover yield depended on soil and agroecosystem characteristics. Corn production under unglaciated, sloping (>6%), erosion-prone, and well-drained soils at Coshocton was more responsive to changes in surface cover than that under glaciated and relatively flat (<1% slope) soils at Hoytville and Charleston. Corn grown on soils at Hoytville may be particularly slower in its response to changes in stover removal because of the soil's high clay content with high shrink-swell potential and poor drainage. The lack of significant differences in corn yield at Hoytville and Charleston suggest

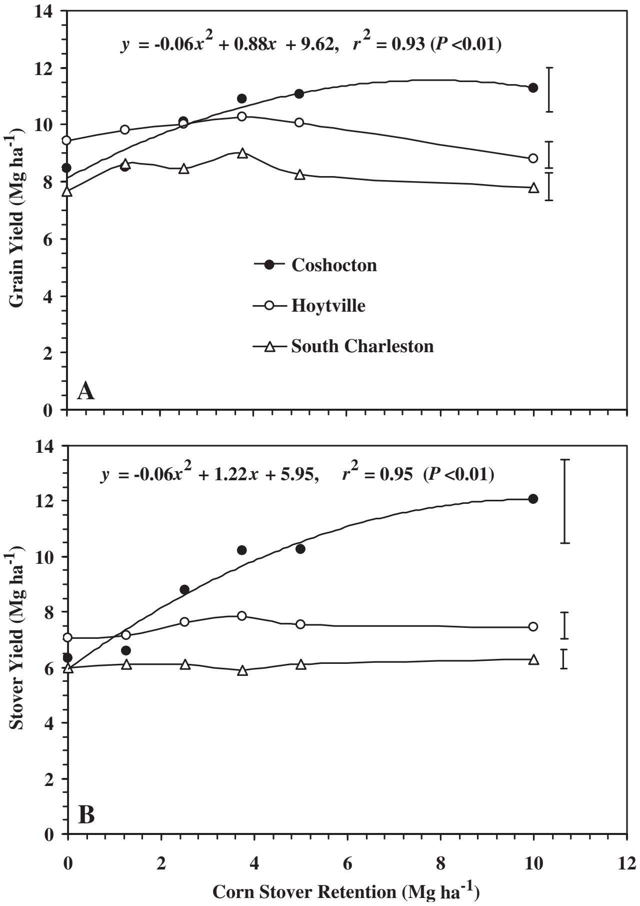

Fig. 7. Corn (A) grain and (B) stover yield under six stover treatments for three no-till sites in Ohio. The error bars represent the $LSD_{0.05}$ for treatment comparisons. The six rates of stover retention of 0, 1.25, 2.50, 3.75, 5.00, and 10.00 Mg ha^{-1} correspond to 0 (T0), 25 (T25), 50 (T50), 75 (T75), 100 (T100), and 200 (T200) % of corn stover, respectively.

that stover removal impacts in some soils may need long-term experimentation (>1 yr) before impacts, if any, are measurable. Despite the uneven emergence and differences in soil θ_v and temperature among treatments at Hoytville and Charleston, differences in grain and stover yields were negligible. Delayed corn emergence in mulched as compared with unmulched soil does not always translate into lower yield. Dam et al. (2005) observed that corn emergence in stover mulched plots was reduced by 18 to 30% relative to unmulched plots, but differences in grain yield between the two treatments were not significant in a loamy sand. Because differences in grain and stover yield among the T200, T100, T75, and T50 treatments were not significant at Coshocton, 50% (2.5 Mg ha^{-1}) stover removal may not negatively affect corn production. This study shows that excessive stover removal, in some soils, can negatively affect corn production within a short time (17 mo) after stover removal from long-term NT plots.

Influence of Soil Properties on Corn Yield using Principal Component Analysis

The significant impacts of stover management on corn yield at Coshocton may be explained by the surprisingly rapid changes in soil physical properties within the 0- to 10-cm depth in addition to soil water and temperature regimes shortly after the stover removal (Table 2). The ρ_b, CI, SHEAR, and TS increased, whereas K_{sat}, k_a, soil water retention capacity at −10 and −30 kPa, MWD, and SOC concentration decreased significantly with increase in stover removal. The stover management effects on soil properties are in accord with the results reported by Blanco-Canqui et al. (2006) for the same study sites. The magnitude of changes in soil properties as a result of stover removal at Coshocton was higher than at the other two sites, indicating that sloping soils may be more susceptible to rapid soil deterioration if stover is removed. These rapid changes in near-surface soil structural properties among treatments most likely altered water, air, and nutrient fluxes, and could explain differences in corn yield.

To identify the dominant soil factors which influenced corn production, PCA was performed on the measured soil properties. Because differences in corn yield were not significant at Hoytville and Charleston, PCA was conducted only for the Coshocton site. The PCA showed that two PCs (PC1 and PC2) with an eigen value >1 explained 75.6% of soil variance. The PC1 explained 65% of the total data variance and PC2 11% (Table 3). The PC1 had very high positive loadings (≥0.77) for CI and SHEAR and very high negative loadings for (<−0.83) for field soil θ_v and TS. The CI with the highest positive loadings (0.95) and communality estimates in PC1 was probably the most sensitive variable affecting crop yield. The high loadings for ρ_b, CI, and SHEAR indicate the high interdependence of soil strength properties. The PC2 had negative loadings for soil temperature and positive for θ_v at −10 kPa, θ_v at −30 kPa, MWD, and SOC concentration. In a similar study,

Table 2. Selected soil properties including bulk density (ρ_b), cone index (CI), shear strength (SHEAR), saturated hydraulic conductivity (K_{sat}), air permeability (k_a), volumetric water content (θ_v), mean weight diameter of aggregates (MWD), soil organic carbon (SOC) concentration, and tensile strength of aggregates (TS) under the six stover treatments for the for the 0- to 10-cm soil depth at Coshocton. The ρ_b, CI, and SHEAR are means averaged across the 3 mo (May, June, and July).

Treatment	Stover rate	ρ_b	CI	SHEAR	K_{sat}	k_a	θ_v (−10 kPa)	θ_v (−30 kPa)	MWD	SOC	TS
	Mg ha^{-1}	Mg m^{-3}	MPa	kPa	mm h^{-1}	μm^2	m^3 m^{-3}		mm	g kg^{-1}	kPa
T200	10	1.18	0.89	26.0	9.63	31.76	0.54	0.46	2.62	32.1	243
T100	5	1.23	1.36	31.7	7.21	18.73	0.49	0.40	2.12	29.6	205
T75	3.75	1.27	1.42	30.7	5.81	19.99	0.49	0.40	2.08	29.3	144
T50	2.5	1.31	1.91	40.7	1.45	0.23	0.47	0.37	1.82	28.7	50
T25	1.25	1.36	2.29	40.7	1.11	0.14	0.44	0.33	1.92	27.9	47
T0	0	1.36	2.28	39.8	0.41	0.10	0.39	0.25	1.50	19.7	44
LSD(0.05)		0.05	0.05	10.4	0.55	12.30	0.06	0.05	0.55	2.9	37

Table 3. Eigen values, variance, loading coefficients, and communality estimates (CE) in the first two principal components (PC1 and PC2).

Properties	PC1	PC2	CE
Eigenvalue	7.79	1.28	
Proportion of the total variance	0.65	0.11	
Cumulative variance	0.65	0.76	
Bulk density	0.70	−0.31	0.59
Field soil water content	−0.83	0.43	0.87
Cone index	0.95	−0.05	0.90
Shear strength	0.77	−0.30	0.69
Temperature	0.64	−0.70	0.90
Saturated hydraulic conductivity	−0.45	0.44	0.39
Air permeability	−0.57	0.54	0.62
Soil water content at −10 kpa	−0.50	0.80	0.89
Soil water content at −30 kpa	−0.55	0.78	0.92
Mean weight diameter	0.04	0.89	0.79
Soil organic C	−0.45	0.69	0.68
Tensile strength	−0.85	0.36	0.85

Shukla et al. (2004) also observed that ρ_b, θ_v at −30 kPa, MWD, and SOC concentration were key variables to explain differences in crop yield. In the present study, changes in soil temperature probably affected stover decomposition and SOC dynamics, whereas gains in SOC concentration improved soil water retention and aggregate stability. The PCs identified K_{sat} and k_a as the least influential soil properties because of their low loadings and communality estimates.

The equations identified by stepwise multiple regressions to predict grain (Y_{grain}) and stover (Y_{stover}) yields for these soils were:

$$Y_{grain} = 12.36 - 0.29PC2 \; (r^2 = 0.71; P < 0.01) \quad [1]$$

$$Y_{stover} = 10.37 - 0.62PC1 \; (r^2 = 0.33; P < 0.01) \quad [2]$$

The Eq. [1] shows that PC2 was a sensitive predictor of grain yield, explaining about 71% of the variability. These results show that soil temperature, water holding capacity and stability of aggregates were the dominant factors controlling grain yield. In contrast, PC1 was an important predictor of stover production and explained about 33% of the variability in stover yield (Eq. [2]). Field θ_v, CI, and TS were among the most sensitive stover yield-influencing variables in PC1. Stover removal reduced θ_v and increased the soil's susceptibility to surface crusting, sealing, and reconsolidation by raindrop impacts, affecting even the micro-scale structural properties of aggregates such as TS. Response of corn yield to changes in soil properties is often variable and site-specific. Studies have shown that soil properties explain about 30% (Kravchenko and Bullock, 2000), 28 to 85% (Jiang and Thelen, 2004), and 24% (Shukla et al., 2004) of the variability in grain yield. This study suggests that rapid changes in near-surface soil structural properties in addition to abrupt changes in soil θ_v and temperature can be critical factors affecting grain and stover production.

CONCLUSIONS

This study shows that stover removal can negatively impact corn production and soil properties within a short time after removal, depending on the soil. Stover removal improves corn emergence and promotes early growth in the first 2 mo following germination. Corn heights among stover removal treatments may, however, catch up to or exceed the control later in the season because of favorable soil water and temperature conditions in mulched plots. The uneven emergence and height of corn are strongly correlated with the stover management-induced changes in soil water content and soil temperature. Results show that stover removal decreases grain and stover yields in sloping, erosion-prone, and unglaciated soils in contrast with glaciated soils on gentle slopes. In sloping soils, stover removal rate >50% (2.5 Mg ha^{-1}) can strongly decrease the grain and stover yields even shortly (17 mo) after stover removal. Changes in soil water content, soil temperature, and near-surface soil structural properties as a result of stover removal explain differences in corn yield using principal component analysis. This study furthers the understanding of short-term stover management impacts on corn production and soil attributes. Additional studies are, however, needed to develop proper stover management strategies and to establish threshold levels of stover removal across these and similar soils.

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